A polar direct drive liquid deuterium-tritium wetted foam ICF target concept

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Executive Summary

For IFE applications, targets will require significant improvements in both yield and gain relative to present day experiments. A promising approach to higher target gain employs the polar direct drive liquid DT wetted foam (PDD-WF) target concept that was introduced in a recent *Physics of Plasmas* publication [1]. With this approach, we find the potential for ICF ignition, propagating burn, and high gain, to be considerably improved compared to current NIF-scale power and energy targets. In a PDD-WF design, PDD of a large diameter spherical target is used to maximize laser coupling, and a thick liquid DT wetted foam shell is used as both the ablator and the fuel layer. The thick wetted foam shell is employed to increase hydrodynamic stability through decreased in-flight aspect ratio (IFAR). The use of DT liquid (instead of DT ice) allows for both ease of fabrication and for flexibility in the density of the central DT vapor region which, in turn allows for control of the hot spot convergence ratio (CR) in a regime that is significantly reduced compared to a DT ice layer implosion [2-4]. The advantages of reduced convergence implosions to suppress hydrodynamic instabilities and mix are well known [5-7], and it is generally acknowledged that the predictive capability of hot spot formation is more robust for a relatively low CR hot spot. Other advantages of wetted foam liquid-fueled targets (as opposed to ice layer targets) include the reduced on-site tritium inventory requirements and the relative robustness for injection into the hellish conditions of a IFE target chamber. In this whitepaper, we propose to follow-up on the findings in Reference 1. Critical first steps would be focused on fulfilling the needs for high resolution, multi-dimensional PDD-WF simulations, target fabrication advances, and experimental tests at OMEGA and the NIF.

Radiation hydrodynamic simulations of a PDD-WF design assuming current NIF drive capabilities using the LANL xRAGE [8,9], LLNL HYDRA [10], and LLE LILAC [11] codes all indicate significantly increased laser-target coupling, and the concomitant improvements in fusion yield. Reference 1 includes a detailed description of a representative 2D HYDRA simulation of a PDD-WF target implosion. An encouraging aspect is that, even with non-ideal symmetry, ignition with a thermonuclear yield of 62 MJ is achieved in the simulation. In a recent LLE *Research and Reviews Seminar* [12], Brian Haines (LANL) presented a 1D xRAGE study of the PDD-WF target that evaluated sensitivities to wetted foam EOS options. The study indicated that, although carbon in the fuel layer reduces compressibility compared to pure DT,

simulations with all three available mixed EOS options result in ignition and high gain. More recently, Cliff Thomas (LLE) performed a similar 1D study using LILAC, which also achieved high gain(s), in the limit CBET and high-mode imprint are mitigated. Relatively modest changes in pulse shape, and/or laser wavelength and bandwidth, were then used to further increase projections at laser energies comparable to NIF.

Thinking ahead to potential Inertial Fusion Energy (IFE) applications [13,14], an important parameter would be the predicted capsule gain, G (defined as thermonuclear energy output / laser energy input). Within the IFE community, it has long been thought that the product of driver efficiency, η, and gain is required to be $\eta G>10$. This assumes that the recycled fraction of the power plant must be less than 25%. In a recent presentation, Mike Campbell [14] pointed out that advances in diode pumped solid state lasers might ultimately result in >20% efficient lasers. Of course, we anticipate that improvements to the preliminary target design [1] will result in higher gains, and the gain of an optimized wetted foam capsule and laser might be ideal for IFE. PDD-WF targets have fewer components than indirect drive targets, and presumably, future target fabrication developments will also bring costs down. Another aspect to consider is the long-term potential for the rapid mass production of 3D printed PDD-WF capsules [15]. Recently, Alex Haid (GA) made an additive manufactured prototype of a PDD-WF capsule using an emergent technology for the one-piece integrated 3D printing of the foam shell, outer skin, and fill tube entrance hole. For IFE applications, additive manufacturing of capsules would seem to have advantages over traditional ICF target fabrication techniques.

The Polar Direct Drive Wetted Foam (PDD-WF) target concept

As discussed in Reference 1, the PDD-WF concept is based on the synthesis of the five following ideas: (1) laser PDD with small beams for enhanced energy coupling to the target; (2) a low peak laser intensity at the absorption surface to suppress laser-plasma instabilities (LPI); (3) the use of emergent 3D printing fabrication for "designer" targets/foams; (4) a liquid DT layer to ease fuel layer fabrication and tune hot spot convergence ratio in a modest range that is not possible with a DT ice layer; and (5) the use of a thick liquid DT ablator layer to increase hydrodynamic stability through decreased IFAR. A pie diagram of a PDD-WF target is shown in Figure 1. A key feature is that the outer portion of the liquid DT wetted foam is the ablator, and the inner portion serves as the fuel layer. The hot spot is initiated in the central DT vapor. A thin CH skin is required on the outer surface to contain the liquid DT. Wetted foam was proposed as an efficient direct drive ablator in [16], and twenty years later, the efficiency was confirmed with more modern computational simulations [17]. The use of wetted foam as both ablator and fuel layer provides a flexible design parameter that can be used to control the IFAR of the implosion. By varying the foam density and shell thickness, the thickness of the imploding wetted foam shell can be controlled to help reduce the deleterious effects of instability growth and hot spot mix. The cryogenic fielding temperature of the liquid DT layer controls the central DT vapor density and, hence, provides a demonstrated ability to control implosion convergence in the range of $10<CR<18$. This experimental concept requires the use of a DT liquid layer (as opposed to a DT ice layer) because the vapor density below the DT triple point is limited to < 0.6 mg/cm^3, producing a high convergence implosion for DT ice. NIF experimental demonstrations of the ability to control the convergence of DT liquid layer implosions are described in [2,4].

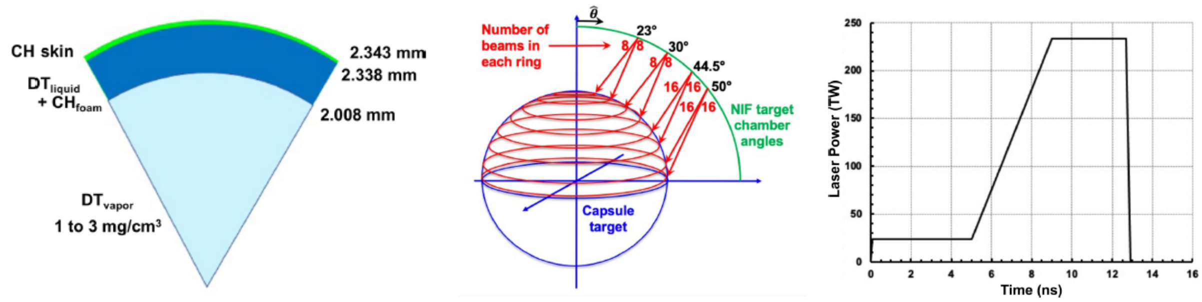

Figure 1: a) The PDD-WF target concept with dimensions used in the 2D simulations of Ref. 1; b) Illustration of the NIF split quad laser pointing geometry used in the 2D simulations of Ref. 1; c) The laser pulse shape used as input in the 2D simuations of Reference 1.

To demonstrate the feasibility for conducting near term proof-of-concept experiments on existing laser facilities, a PDD-WF design driven by a NIF laser pulse that employs 192 narrow beams pointed in a polar direct drive laser configuration is shown in Figure 1b. The NIF's laser beam quads are located on the target chamber walls in four polar angle rings at 23.5, 30, 44.5 and 50 degrees from each pole and contain 4, 4, 8 and 8 beam quads, respectively, equally spaced longitudinally in phi around the target chamber. For this design, each individual beam is pointed at a unique location on the capsule surface. The upper and lower pairs of beams from each quad are split to point at different polar angle positions on the capsule resulting in eight different polar rings of beams on the capsule. These angles were adjusted to minimize the variation in velocity of the shell with respect to polar angle as measured prior to shell deceleration. The polar angles for the sub-rings of beams are 12.5, 30, 37.5, 41.5 54, 65.5, 79 and 85.5 degrees. It is assumed that the beam pairs are also split in longitudinal angle phi to achieve equal spacing of the beams from each sub-ring on the capsule surface. The baseline design assumes equal drive power on all 192 beams. Any observed P_2 asymmetry in the design is then tuned out by adjusting the power in the 23.5 degree beams. Such asymmetries can arise when changing the material properties of the shell. For the Reference 1 simulation, an 8% increase in the power of the 23.5 degree beams was used. For NIF experiments, P_2 and/or P_4 shimmed targets might also be useful. The maximum drive power during the laser pulse was 223 TW and the integrated energy in the pulse was 1.4 MJ, significantly lower than the current energy and power available in NIF. The laser pulse shape is shown in Figure 1c. The early-time "foot" of the laser pulse creates a blow-off plasma that is used to set the position of the laser absorption region beyond the original capsule radius. As shown in Reference 1, radiation hydrodynamic simulations indicate that the laser absorption region remains at a diameter of about 5-6 mm throughout the laser pulse. This results in a low average intensity (<250 TW/cm^2) in the laser absorption region. In previous NIF experiments with a similar pointing scheme, spot size, and laser intensity, the laser absorption has been measured to be 98-99% [18,19].

Density contours of the imploding, inner portion of the wetted foam region are shown in Figure 2 for times of 11, 12, 13, and 14 ns. There are some noticeable angular density fluctuations in the imploding shell. However, in a simulation in which the number of angular zones is doubled, it appears that the fluctuations and mode amplitudes are uncorrelated with zoning. Future work could improve resolution, and further refine these predictions in 2 and 3-D.

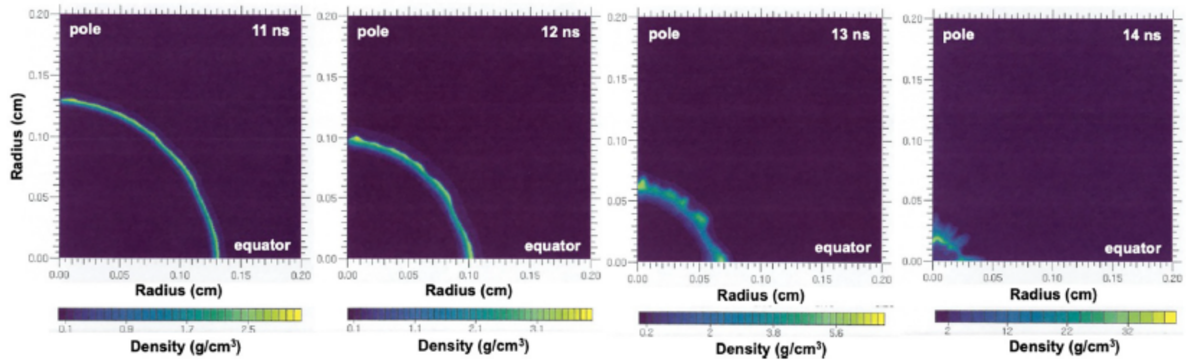

Figure 2: Density contours at times of 11, 12, 13, and 14 ns during the implosion.

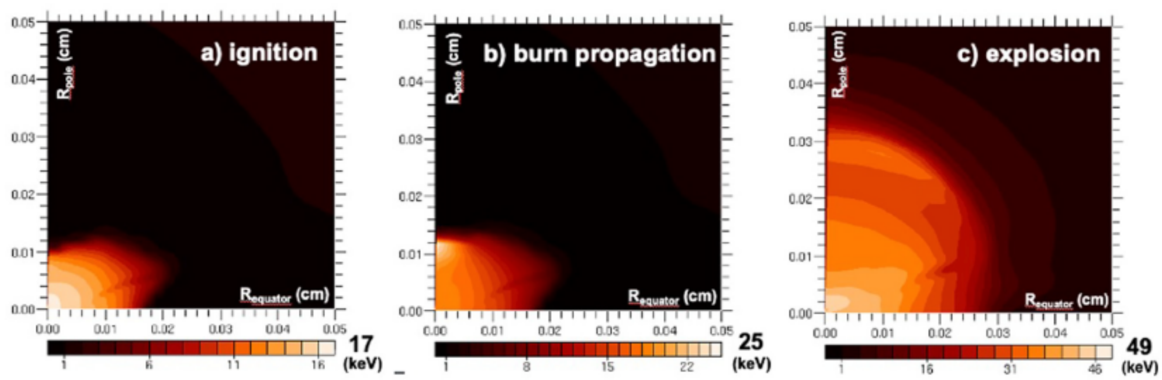

Figure 3: a-c) ion temperature at times of ignition, burn propagation, and thermonuclear explosion, respectively.

Clearly, the shape of the imploding shell at the end of the laser pulse in this simulation indicates that the pole was driven harder than the equator. Other 2D simulations indicate that the pole/equator shape can be adjusted via changes in the laser cone power fraction. However, even with the significant Legendre P_2 mode asymmetry in this simulation, the hot spot ignites. Details of the ignition and thermonuclear burn phases of the simulation are shown in Figure 3. At the time of ignition (Figure 3a), the hot spot (region with $5 < T_{ion} < 15$ keV) is quite large compared to a typical high CR indirect drive DT ice layer implosion (hot spot volume ~100X indirect-drive). Within about 20 ps after ignition (Figure 3b), a burn propagation wave heats the dense polar fuel to an ion temperature exceeding 20 keV. At about 80 ps after ignition (Figure 3c) the thermonuclear explosion phase is underway with most of the DT/lattice plasma heated to an ion temperature above 40 keV. The encouraging aspect is that, even with non-ideal symmetry, ignition and a thermonuclear yield of 62 MJ is achieved in this PDD-WF simulation. Grading the density of the foam versus radius might enable even higher performance, but will depend on tradeoffs in 1-D energetics and 2-D stability that need further study. Key parameters from the simulation are shown in a detailed table included in Reference 1.

The PDD-WF targets are made possible using an emergent technology for the one-piece integrated 3D printing of the foam shell, outer skin, and fill tube entrance hole. Such an additive manufacturing fabrication technique has been used to produce a 3D printed prototype of a PDD-WF capsule (Figure 4). The prototype is based upon the PDD-WF capsule specifications and dimensions shown in Figure 1. A photograph of the prototype capsule is shown in Figure 4a.

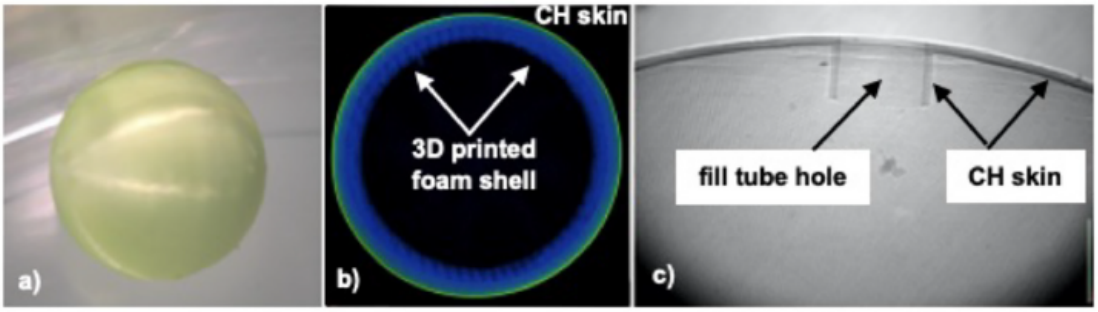

Figure 4: a) PDD-WF capsule 3D printed with the dimensions specified in Figure 1; b) full diameter tomograpic image of the capsule; c) detail of the fill tube region (images courtesy of Alex Haid, GA).

Figure 4b is a full diameter tomographic image of the capsule. The blue region is the foam (or "lattice") shell (density is 20 mg/cm^3), and the green is the outer CH skin. The tomography data can be evaluated for uniformity of the thickness, roundness, and density of the lattice and skin. Figure 4c is a radiograph showing details of the fill tube region. The CH skin extends halfway into the fill tube hole so that the fill tube can be attached while leaving enough space for the liquid DT to flow into the CH foam. The method used to 3D print is called "2 Photon Polymerization" (2PP). The prototype target shown in Figure 4 was printed with a 2PP process that resulted in a foam shell having a composition of approximately $C_{11}H_{12}O_3$ (~12% oxygen). However, there are modest advantages to reducing the oxygen content in the foam, and efforts are underway to develop a process that can print a pure CH foam shell. Higher-Z dopants, including silicon, have been shown to mitigate hot electron production in experiments at OMEGA at NIF, and might also be a topic of study.

Proposed Research on the PDD-WF Concept

The PDD-WF concept clearly has promise for achieving the gain levels required for IFE, though most of the detailed findings are still preliminary. Much work remains to be done in the areas of target design, sensitivity studies, and target fabrication prior to experimental demonstration of 10's of MJ yield at the NIF. An additive manufactured prototype of a PDD-WF capsule has been fabricated using an emergent technology for the one-piece integrated 3D printing of the foam shell, outer skin, and fill tube entrance hole. For future work, we propose that such prototype capsules can be characterized for levels of imperfections in foam density and thickness uniformity, out-of-roundness, and outer skin roughness. In an iterative feedback process, 2D and 3D simulations can be used to determine tolerances and specifications on these various target imperfections, and to study effects of laser nonuniformities (imprint) and power balance. Off-line cryogenic experiments must be done to explore and understand the liquid DT wetting characteristics of the new type of 3D printed CH lattice class of foams. Appropriate PDD cryogenic capabilities must be demonstrated at NIF. Finally, although it is an old idea, a new interest in the use of wetted foam as an ablator material opens up opportunities for experimental demonstration and characterization of the concept at Omega and NIF. Cryogenic wetted foam planar ablation measurements at Omega, along with integrated wetted foam capsule implosion tests at Omega and NIF would be important components of the PDD-WF experimental plan.

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